Quark-antiquark production from classical fields and chemical equilibration

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Abstract

We compute by numerical integration of the Dirac equation the number of quark-antiquark pairs produced in the classical color fields of colliding ultrarelativistic nuclei. The backreaction of the created pairs on the color fields is not taken into account. While the number of $q\bar{q}$ pairs is parametrically suppressed in the coupling constant, we find that in this classical field model it could even be compatible with the thermal ratio to the number of gluons.

Outline

- Background, context
- How classical fields produce fermion pairs[1]
- First results[2]
- Conclusions

Motivation

- Heavy quark production: doable perturbatively, but do the strong color fields change the result?

- Chemical equilibration, light quark production? ▶ Essential for understanding how and if the CGC turns into (thermalized) QGP.

[1] F. Gelis, K. Kajantie and T. Lappi, Phys. Rev. **C71**, 024904 (2005), [hep-ph/0409058].
[2] F. Gelis, K. Kajantie and T. Lappi, hep-ph/0508229.

Related calculations

- Analytical calculation in MV model: lowest order and pA: Gelis, Venugopalan, Fujii[3,4]
- $\mathbf{k}_T$–factorized calculation, "CGC" distributions: Kharzeev, Tuchin[5,6]
- Corresponding calculation in QED can be done analytically to all orders: Baltz, Gelis, McLerran, Peshier[7,8]
- Analytical calculation in a more general setting by Dietrich[9]
- This is not the constant field Schwinger mechanism, but gluons with $\mathbf{k}_T \sim Q_{\mathrm{s}}$ (Too many references to note here.).

[3] F. Gelis and R. Venugopalan, Phys. Rev. **D69**, 014019 (2004), [hep-ph/0310090].

[4] H. Fujii, F. Gelis and R. Venugopalan, hep-ph/0504047.

[5] D. Kharzeev and K. Tuchin, Nucl. Phys. **A735**, 248 (2004), [hep-ph/0310358].

[6] K. Tuchin, Phys. Lett. **B593**, 66 (2004), [hep-ph/0401022].

[7] A. J. Baltz and L. D. McLerran, Phys. Rev. **C58**, 1679 (1998), [nucl-th/9804042].

[8] A. J. Baltz, F. Gelis, L. D. McLerran and A. Peshier, Nucl. Phys. **A695**, 395 (2001), [nucl-th/0101024].

[9] D. D. Dietrich, Phys. Rev. **D70**, 105009 (2004), [hep-th/0402026].

Background field from MV, KMW model

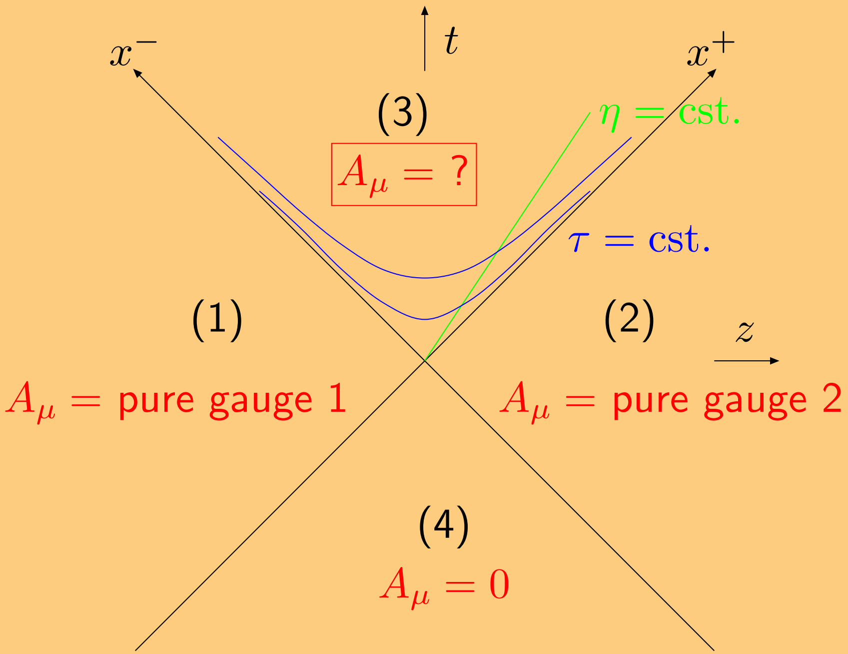
The MV[10] model, collision of two ions studied analytically by KMW[11] and numerical formulation by Krasnitz & Venugopalan[12]

$$[D_\mu, F^{\mu\nu}] = J^\nu,$$

$$J^\mu = \delta^{\mu +}\rho_{(1)}(\mathbf{x}_T)\delta(x^-) + \delta^{\mu -}\rho_{(2)}(\mathbf{x}_T)\delta(x^+),$$

$$\langle \rho^a(\mathbf{x}_T)\rho^b(\mathbf{y}_T)\rangle = g^2\mu^2\delta^{ab}\delta^2(\mathbf{x}_T - \mathbf{y}_T).$$

$$g^2\mu \sim Q_\mathrm{s} \quad \text{(very roughly)}$$

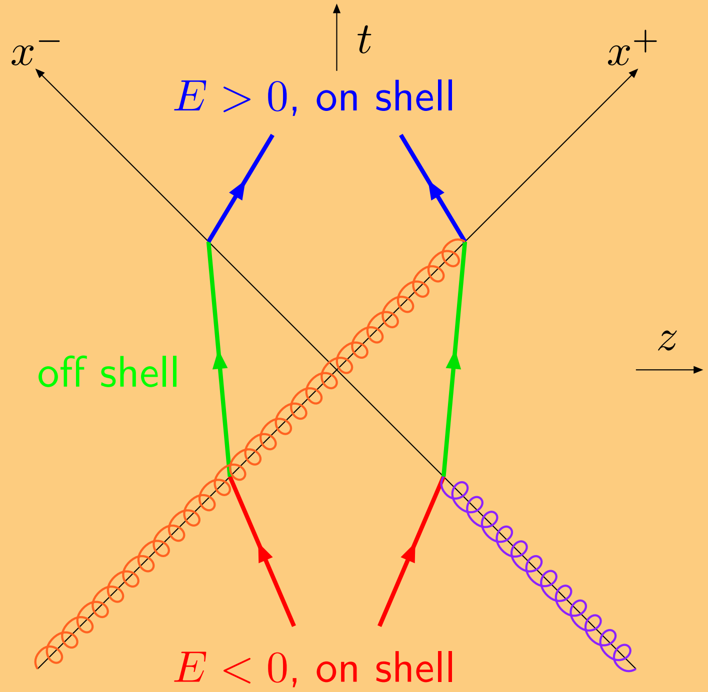


[10] L. D. McLerran and R. Venugopalan, Phys. Rev. **D49**, 2233 (1994), [hep-ph/9309289].
[11] A. Kovner, L. D. McLerran and H. Weigert, Phys. Rev. **D52**, 3809 (1995), [hep-ph/9505320].
[12] A. Krasnitz and R. Venugopalan, Nucl. Phys. **B557**, 237 (1999), [hep-ph/9809433].

Dirac equation in background field

Solve Dirac equation in backgroud field. (Think: Dirac sea.)

- Initial condition: negative energy plane wave $e^{iq\cdot x}v(q)$.
- Integrate D.E. forward in time (equivalent to retarded, not Feynman, propagator).
- Projection to positive energy states $e^{-ip\cdot x}u(p)$ gives number of quark pairs produced.



In infinite energy case: Two separate branches of the solution; (amplitude linear superposition of two terms; think of u, t-channels in Abelian case).

Solving the Dirac equation

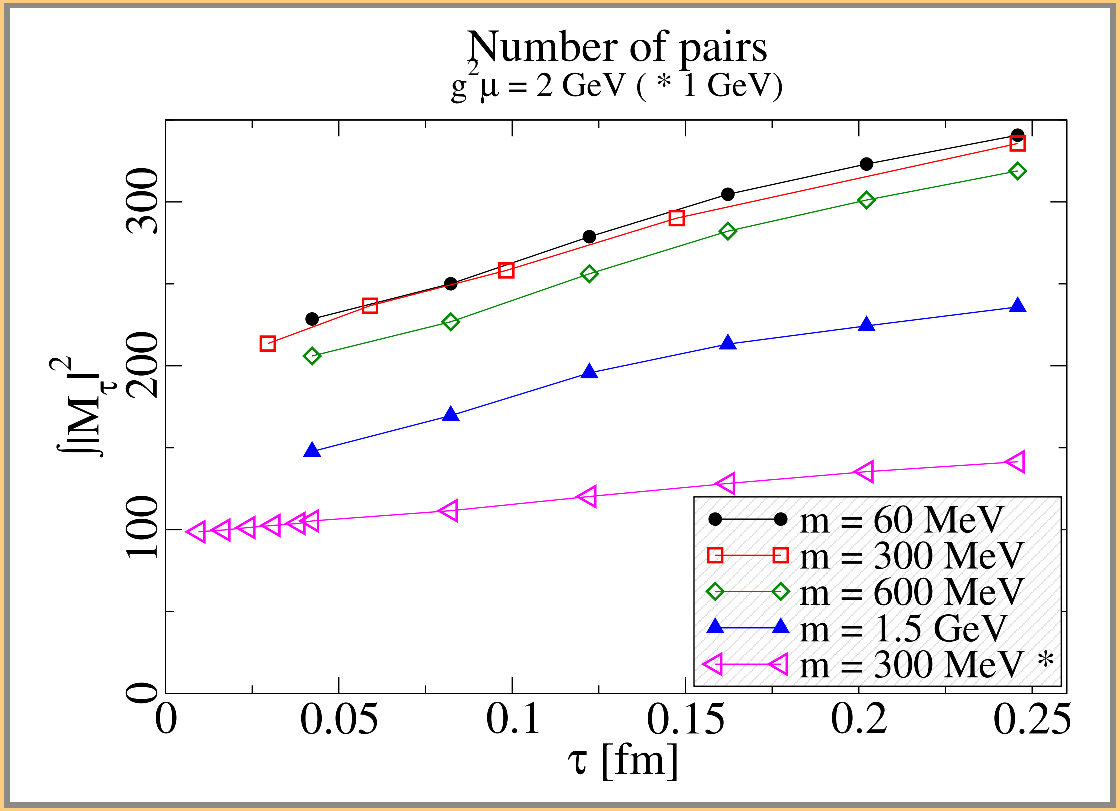
- Hard sources in initial condition only ▶ time coordinate τ.
- Must represent longitudinal momenta at $\tau = 0$ ▶ longitudinal coordinate z, not η.
- Boost invariant background field.
  - Amplitude depends only on $y_q - y_p$.
  - But there is a correlation between y_q and y_p ▶ numerical calculation must be 3+1-dimensional.

Have to use *implicit* method in discretizing transverse direction, details[1].

Parameters: $g^2\mu$ (bg field), R_A (system size), and m (quark mass).

[1] F. Gelis, K. Kajantie and T. Lappi, Phys. Rev. **C71**, 024904 (2005), [hep-ph/0409058].

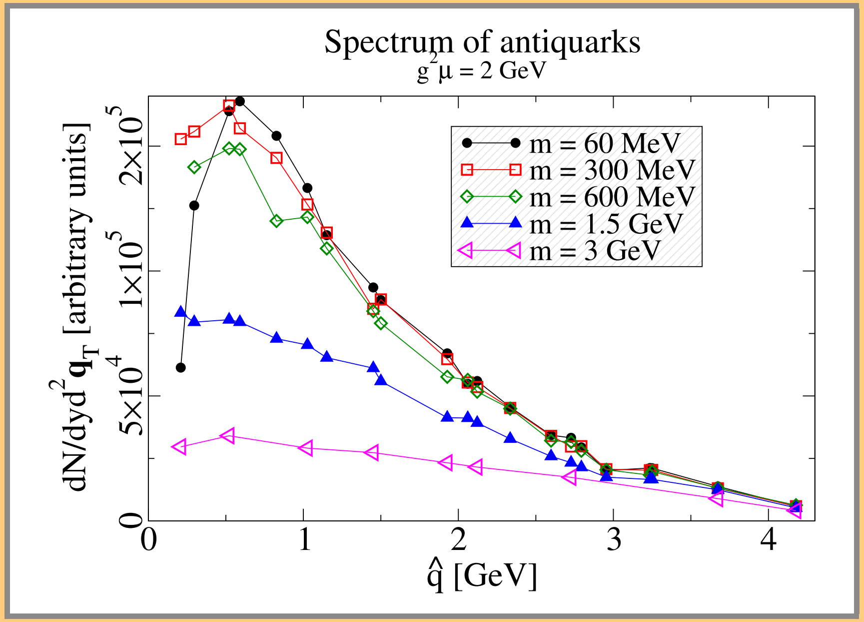
Number of pairs, time dependence

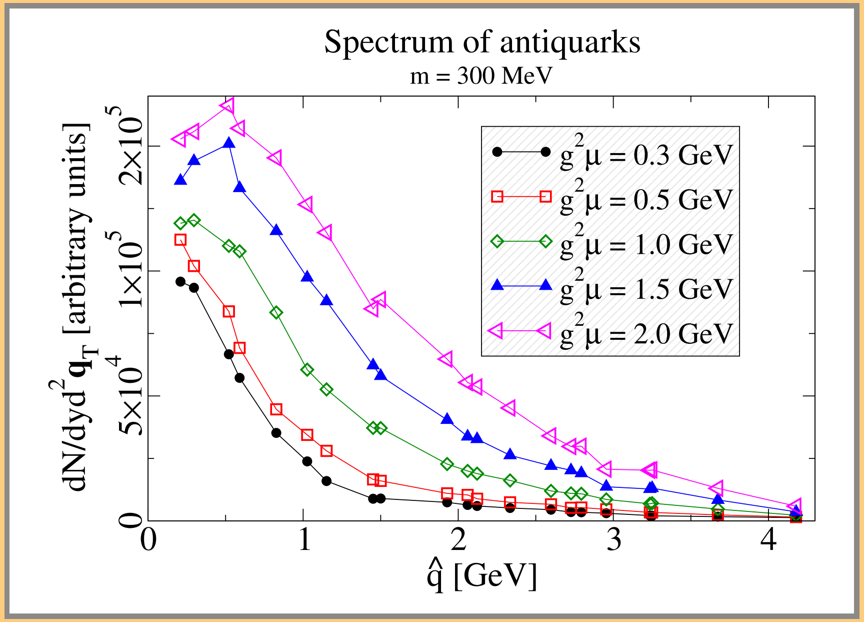


Most of the pairs are produced at $\tau = 0$, then the number increases in the background field.

Note: This is for one flavor of mass m and one unit of rapidity y.

(Anti)quark spectrum

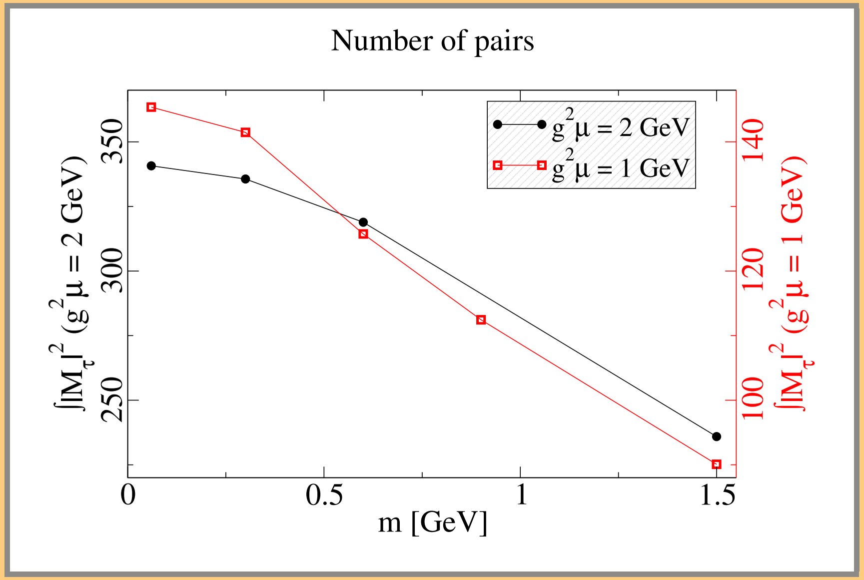


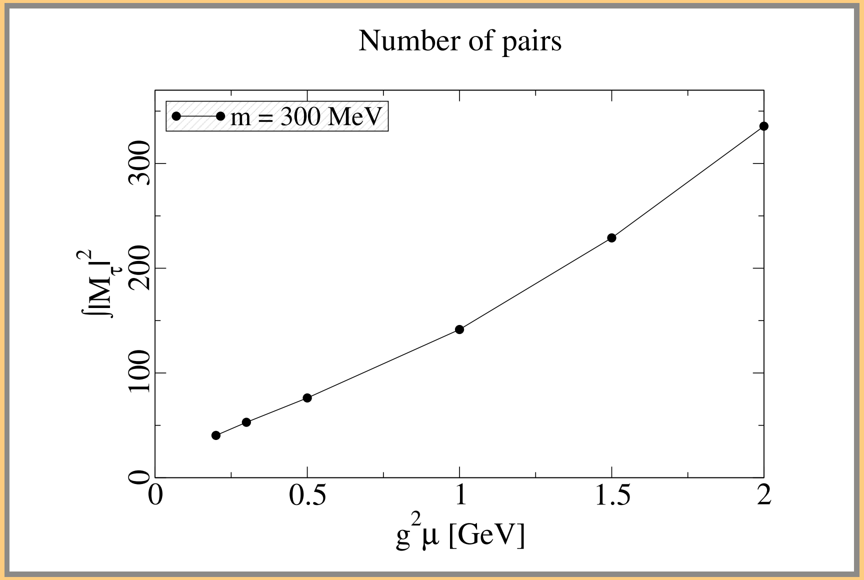


Different masses. Different saturation scales

This is on 180^2–lattice, large finite a–effects expected. Lattice cutoff in $\hat{q}$ is at $4.2\mathrm{GeV}$, expect lattice effects starting from $2\ldots3\mathrm{GeV}$.

Number of pairs, dependence on mass and $g^2\mu$



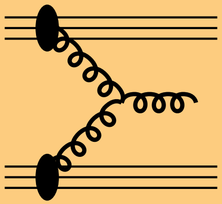


Dependence on mass

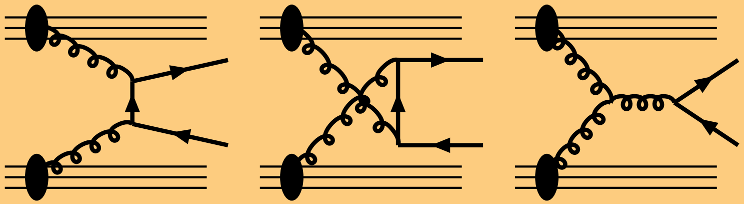
Dependence on $g^2\mu$

Discussion: does this make any sense?

We are now calculating:



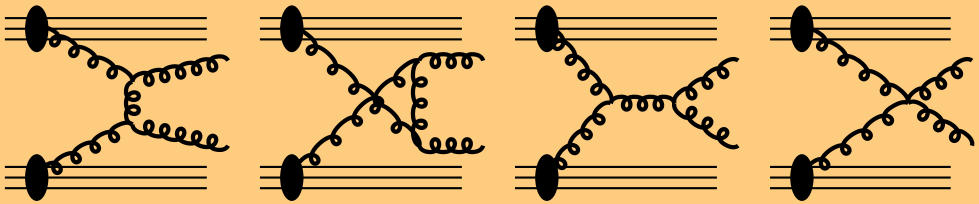
$\mathcal{O}(\frac{1}{\alpha_s})$ and



$\mathcal{O}(1))$

Different orders in g, but $g = 2$: no surprise that result is big.

For consistency should also calculate the first quantum correction to gluon production:



$\mathcal{O}(1)$

Phenomenology

I.e. what does this result mean if one does take it seriously?

Assuming that the subsequent evolution of the system conserves entropy $\sim$ multiplicity we should have ~ 1000 particles (gluons, quarks, or antiquarks) in the initial state.

- If these are all gluons, we need $g^2\mu \sim 2\mathrm{GeV}$[13].
- If also quarks are amply present, we could have $g^2\mu \sim 1.3\mathrm{GeV}$, ~ 400 gluons, $\gtrsim 100 N_\mathrm{f}$ quarks and $\gtrsim 100 N_\mathrm{f}$ antiquarks, close to the thermal ratio $N_g/N_q = 32/9 N_\mathrm{f}$.

[13] T. Lappi, Phys. Rev. **C67**, 054903 (2003), [hep-ph/0303076].

Conclusions

Quark pair production from classical background field of McLerran-Venugopalan model studied by solving the 3+1–dimensional Dirac equation numerically in this classical background field.

- Number of quarks produced large (► chemical equilibration)
- Mass dependence surprisingly weak because large $\mathbf{k}_T$ modes sensitive to lattice effects, no conclusions on heavy quarks yet.
- Numerical computation still continuing.